SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: 3rd Int. Geodetic Symp. on Doppler Geodetic Positioning LasCruces, NM	2. GOVT ACCESSION NO.: AD A110510
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): An Unbiased Analysis of the Doppler Coordinate Systems	5. TYPE OF REPORT & PERIOD COVERED: N/A
	6. PERFORMING ORG. REPORT NUMBER: N/A
7. AUTHOR(s): Muneendra Kumar	8. CONTRACT OR GRANT NUMBER(s): N/A
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Defense Mapping Agency Hydrographic/Topographic Center, Washington, DC 20315	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: N/A
11. CONTROLLING OFFICE NAME AND ADDRESS: DMAHTC ATTN/ PPTD (Tech. Pubs.) Washington, DC 20315	12. REPORT DATE: February 1982
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 25	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

LEVEL II

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

DTIC ELECTE FEB 5 1982 D

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Analysis
Coordinate Systems
Unbiased
Doppler

82 02

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(see reverse side)

AD A110510

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ABSTRACT

AN UNBIASED ANALYSIS OF DOPPLER COORDINATE SYSTEMS

by

Muneendra Kumar

From its modest beginning (and with conservative goals) in 1953, the Doppler survey technique has achieved remarkable progress. To obtain sub-meter absolute accuracies, meaningful and realistic, it is very important that we take a fresh look at the precision and accuracy of different coordinate systems obtained through Doppler surveys and their interrelationship.

The Dopler system has undergone at least five major revisions, or improvements, in its definition since original inception. Some of the so-called "minor" modifications of the past have not been well documented and corresponding rigorous updating of the software in many instances is also lacking. The actual impact and contribution of each such modification and the absence of proper updating towards inner consistency are not negligible in the present sub-meter era.

The questions whether (1) the Broadcast Ephermeris (BE) based coordinates are either automatically calculated in the WGS 72 datum or derived with respect to the reference ellipsoid for the WGS 72 datum; (2) the BE system, except for a small bias, is close to the NSWC 9Z-2 system; (3) the BE based coordinates are in the NWL 9D system or "strictly speaking" in the modified NWL 10D system; (4) the Doppler coordinate system was NWL 9D prior to June 1977 and is NSWC 9Z-2 now; and (5) the coordinate system NWL 9D (and/or NSWC 9Z-2) is geocentric or has a significant Z-axis bias, are still floating around. The net result is misunderstanding and misinterpretation for many users.

The present paper tries to highlight some of the related problems and to answer them as well as possible. In the author's opinion, some of the questions cannot be properly authenticated one way or the other at this time without first upgrading the consistency of all types of data analyzed and without proper refinement of the involved geodetic definitions.

AN
UNBIASED ANALYSIS
OF
DOPPLER COORDINATE SYSTEMS

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ABSTRACT

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The Doppler system has undergone at least five major revisions, or improvements, in its definition since original inception. Some of the socalled "minor" modifications of the past have not been well documented and corresponding rigorous updating of the software in many instances is also lacking. The actual impact and contribution of each such modification and the absence of proper updating towards inner consistency are not negligible in the present sub-meter era.

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The present paper tries to highlight some of the related problems and to answer them as well as possible. In the author's opinion, some of the questions cannot be properly authenticated one way or the other at this time without first upgrading the consistency of all types of data analyzed and without proper refinement of the involved geodetic definitions.

1. INTRODUCTION

The U.S. Navy Navigation Satellite System (NNSS and/or NAVSAT) was originally established in 1959 (Guier and Weiffenbach, 1960) to provide a real-time navigational position with an accuracy goal of $\pm$100 m. Soon, it became evident that this transit satellite system could be used for geodetic point positioning. In 1962 a project with a conservative goal of $\pm$10 m accuracy was initiated to develop this capability (Anderle, 1978). From its modest beginning with 50 m geodetic accuracy in 1963, the Doppler survey technique has achieved remarkable progress. The current best estimate for the system accuracy is about 1 m in each positional component. In the 1980's the geodetic goals look forward to sub-meter absolute accuracies.

The accuracy expections at sub-meter levels, meaningful and realistic, are still quite ambitious in the very near future. To achieve this it is necessary to carefully analyze and understand the complex changes, evolution and development of the Doppler technique through the years and the corresponding impact on the involved geodetic definitions and the internal consistency of the system. It is also very important to take a fresh look at the precision and accuracy of different coordinate systems which are available (or obtained) through various Doppler survey procedures and their interrelationship.

The present paper tries to highlight some of the related problems and the resulting misunderstandings and misinterpretations. An effort has also been made to answer the following questions as well as possible.

(1) Are the Broadcast Ephemeris (BE) based coordinates automatically calculated in the World Geodetic System (WGS) 72 datum or derived with respect to the reference ellipsoid for the WGS datum?

(2) Is the BE system, except for a small bias, close to the NSWC 9Z-2 system?

(3) Are the BE based coordinates in the NWL 9D system or "strictly speaking" in the modified NWL 10D system?

(4) Whether the Doppler coordinate system was NWL 9D prior to June 1977 and is NSWC 9Z-2 now?

(5) Is the coordinate system NWL 9D (and/or NSWC 9Z-2) geocentric or does it have a significant Z-axis bias?

2. HISTORICAL EVOLUTION

An informative treatise including most of the important and pertinent details about the mathematical model, equations of motion, observation equation and the parametric solution of the Doppler system is available in Anderle (1976) and at least five major revisions, or improvements, in the definition of the system since its original inception, are easily identifiable. These

system definitions and redefinitions over the years occurred (or followed) corresponding to the changes in the gravity field, in addition to other parametric definitions and systematic error modeling modifications, used in the computations. It will be worthwhile to include these details here for highlighting their contributions.

a. Gravity Field

The different gravity field revisions in the Doppler systems, since the original one, are summarized in Table 1.

It is estimated that the satellite positions, computed with the different gravity fields, change about 5 m (Anderle, 1976) with a corresponding variation in station positions (computed from the new ephemeris) to about 2 to 3 m (Anderle, 1976; Anderle, 1980).

b. Coordinate Systems

The station coordinates of the TRANET base network have changed, corresponding to gravity field revisions in recent years (Table 2). The differences of NWL 9C coordinates from the NWL 8F were about 3 m (Anderle, 1976).

For the latest revision from NWL 9D to NSWC 9Z-2, a change of about 2 m was expected (Anderle, 1976) and the actual variations (later computed) were of the order of 1.5 m in each axis world wide (Anderle, 1980). Table 3 gives the result of a seven parameter transformation between NWL 9D and NSWC 9Z-2 system for 14 TRANET stations which have been in use continuously,

both before and after June 1977 to compute the precise satellite positions by the Defense Mapping Agency (DMA). If any investigator is seeking meter and/or sub-meter accuracies in the Doppler derived station positions the difference between the NWL 9D and NSWC 9Z-2 systems is not negligible.

Parallel to the evolution of a precise Doppler coordinate system (Table 2), the NNSS satellites have been transmitting (or broadcasting) the satellite positions in real-time. Even though the intentions have been to maintain the Precise Ephemeris (PE) and the Broadcast Ephermeris (BE) in the same system (or as close to each other as possible), the two systems to date are different and it can be clearly established here that the present BE coordinate system is "Modified" NWL 10D and is based on the WGS 72 gravity field (Jenkins and Leroy, 1979; Yionoulis and Eisner, 1980). The real impact on the station coordinates, obtained using the BE, and their relationship to the "precise" Doppler coordinate system is further discussed in Section 3.1.a.

3. ANALYSIS OF DOPPLER COORDINATE SYSTEMS

In the following discussion the paper first analyzes the various Doppler coordinate systems and their impact on the geodetic determination of station coordinates in an inter-comparative manner. Additional comments have also been included on the relationship between the WGS 72 and the Doppler coordinates obtainable through the broadcast and precise systems. Then, the geocentricity of the NSWC 9Z-2 system in the absolute sense has been investigated.

The analysis has been restricted here to the problems related to geodetic point positioning with specific remarks to the goal of sub-meter accuracies

in the 1980's. The effort tries to remove the gray areas between the system definitions and the resulting misinterpretations for many users.

3.1. Inter-comparison of Doppler Systems

Classical problems in optimizing the Doppler geodetic control accuracy can be associated to specific conditions of data processing, the use of BE or PE and the survey adjustment techniques together with the involved constraints. Even in a particular adjustment or data reduction method for station positions, the mathematical model varies from agency to agency and sometimes within an agency (Anderle, 1976). It can also be inferred that the overall impact of the various changes, revisions and improvements of the Doppler system over the years would significantly vary for local, regional, and global control, both for precision and accuracy and the same are definitely not negligible in the present sub-meter era.

3.1.a. The BE System

The Broadcast Ephemeris is generated through NNSS satellite tracking by the four U.S. stations, non-global in their locations, and as such the geocentricity of this system can not be "strictly" ensured. The associated standard errors to the satellite positions are estimated as 19, 14 and 4 m in the in-track, cross-track and radial directions and internal consistency for three dimensional case as 10, 11, and 15 m (Arur, 1979). Ziegler (1979) also found the BE point position solution means to be a factor of 10 to 20 times worse than the TRANET with correspondingly higher variances.

The most common method for station positioning based on the BE is the short arc technique (or its simplified versions, translocation and semi-short arc) and in this approach the "constraints" applied through the "known" station or stations coordinates (Mueller, et al., 1975) play a major role in defining the coordinate system of the network. Ashkenazi (1979) found the difference between the BE derived coordinates over Europe to the precise system (presumably the NSWC 9Z-2) to be -3 m in X, -11 m in Z and -0.4 ppm in scale. A similar study was recently carried out at the Defense Mapping Agency, Hydrographic/Topographic Center (DMAHTC) and the results are given in Table 4. These transformation values (together with Askenazi's results) clearly indicate that the differences in the BE and PE coordinate systems would vary from one project to another and are significant. For geodetic applications, even when precision and accuracy requirements are only around 1 to 5 m level, the two system can not be considered the same. Each project has to be evaluated independently.

In case a "point positioning" solution (Brown, 1976) is carried out, e.g., with a Magnavox 1502 instrument (Magnavox, 1979) without any external constraints, the station coordinates would then have to be in the "Modified" NWL 10D system (Jenkins and Leroy, 1979). A study of such a network, for its relationship to other systems, may indicate some interesting results. However, Brown (1975) shows an expected relative accuracy of only 3 to 5 m using this approach.

The positions of the Herndon Station, Virginia, when computed with the BE (in the point positioning mode) and compared against the one from the PE, have shown significant differences ranging from 7 to 16 m (Leroy, 1976).

3.1.b. The PE System

All solutions for station positions, which utilize the Precise Ephemeris, are done operationally in the "point positioning" mode. The satellite orbit, in this procedure, is assumed perfect and thus held fixed. However, the mathematical models (used by various agencies, viz., DMAHTC and NSWC) have not all been consistent (Anderle, 1976).

These "individually" established Doppler stations can not be taken to constitute a rigid network. The relative accuracy of such a station framework would also be inferior to a similar one obtained through the short arc technique (Brown, 1976).

Further, if the change in the Doppler coordinate system is taken into consideration (Tables 2 and 3; Anderle, 1980), the regional and absolute biases of the order of 1 to 2 m between NWL 9D and NSWC 9Z-2 systems can be expected.

3.1.c. The WGS 72 System

The inter-relationship between the Doppler system of date and the WGS 72 was originally established as a requirement of the World Geodetic System 1972 project (Seppelin, 1974a). Since then the Doppler system has undergone three changes, e.g., of two gravity fields and one coordinate system. The impact of these changes together with "other" modifications over the last 10 years is non uniform globally, especially if one is considering meter and/or sub-meter accuracy levels.

In view of the section 3.1.a., the relationship between the Doppler station coordinates based on the BE and the WGS 72 system is still more complex. The only straight forward and practical procedure available is then to convert the Doppler three dimensional coordinates (X, Y, Z) to the WGS 72 ellipsoid. Any other interpretation of a simple transformation between the BE and the WGS 72 Systems (section 1) would be erroneous.

3.2 The Z-Axis Bias

The question whether the Doppler coordinate system as defined by the PE is geocentric or not has been under investigation for quite some time. Anderle (1974) and Rapp and Kummel (1976) found the Doppler origin to be coincident with the center of mass of the earth within the noise level of the system.

However, investigators (Huber, 1979 a and b; Hothem, 1979; Learch et al., 1979; Grappo, 1980) have indicated the presence of a 5 m Z-axis bias (the origin to be "below" the XY plane) in the Doppler system. Another study (Marsh and Williamson, 1980) found it inconclusive whether the Z error is in the GSFC system or Doppler or partially in both. Schaab and Groten (1979) have shown that the quality of data available through the various earth gravity models can not still fully corroborate the assumption that a significant part of the regional geoidal height differences between different systems can be explained by origin shift.

Anderle (1980) quoting the work of Mark Tannenbaum shows that the change of 0.5 km^3/sec^2 in GM can produce Z coordinate shift of about 2.2 m and found

that the recomputed Doppler coordinates using the latest GM value of 398600.5 km^3/sec^2 did not exhibit a bias in Z.

The author, while on special assignment to DMAHTC from National Geodetic Survey (NGS) during 1980-81, studied this problem to elaborate on the works of Huber (1979) and Grappo (1980) recently performed wi. 'n the DMA. One extremely obvious and interesting feature noticed was the timing of the above investigations, viz, Anderle (1974) and Rapp and Rummel (1976) are before the date 15 June 1977 (i.e., the studied system is NWL 9D) while Huber (1979 a and b) and Grappo (1980) are after the "change", while using the same technique. Table 3 also shows a partial explanation of this two system problem.

However, even neglecting this time factor, the author found that both Huber (1979 a and b) and Grappo (1980) started with the mathematical model of Rapp and Rummel (1976) but got significantly different results. Huber and Grappo in their studies even d'ffered about 2 m between themselves in the computed Z-shifts. All these studies had "global" data which differed in the number of Doppler stations included. It seemed difficult to attribute the Z-shift or its variation from 0 to 5 m only to the number of stations included. A close study showed more subtle differences and the most important ones are discussed in the following sub-sections.

3.2.a. Rapp and Rummeleiner (1976)

The authors in their study model gravimetric undulation into three components, N_1, N_2, N_3 (Rapp and Rummel, 1975) where the contribution from N_3 is made practically equal to zero by manipulating the cap size at the point

of interest. The contribution of N_2 is very significant and can not be ignored (Rapp, 1981). The final adjustment also includes the zero order term N_0.

The gravity field used is GEM 8 (Wagner, et al., 1976) and the Doppler system NWL 9D (scaled by -0.4 ppm) is directly compared.

3.2.b. Huber (1979b)

Huber computes only the term N_1 and includes the zero order N_0 also. The model does not include N_2 and the gravity field used for comparison is GEM 10B (Lerch, et al., 1978).

The Doppler system NSWC 9Z-2 was not compared directly. The XYZ coordinates were first scaled by -0.4 ppm and this scaled set was then transformed to the WGS 72 system. In establishing the transformation parameters between the NWL 9D and WGS 72 systems the scale bias was already considered (Seppelin, 1974b) and as such the above scale correction of -0.4 ppm becomes a duplication.

3.2.c. Grappo (1980)

The author considers only the term N_1 and does not include N_2 and N_0. The gravity fields used for comparision are GEM 10A (could not be GEM 10 as referenced) and GEM 10B (Lerch, et al., 1978).

The Doppler system NSWC 9Z-2 coordinates were first corrected for antenna offset and for GM value change from 398601.0 to 398600.5 km^3/sec^2 (Anderle,

1980). This set was then transformed to the WGS 72 system (see section 3.2.b.; Seppelin, 1974b).

A study has been initiated recently at DMAHTC to re-investigate the relationship between the Doppler system NSWC 9Z-2 (without transforming it to the WGS 72 system) and the gravity fields GEM 8 and GEM 10B. In the present study all efforts will be made to set up a mathematical model consistent to Rapp and Rummel (1976) as discussed in section 3.2.a. and to include some additional investigations. At this time the results are not available for presentation.

4. SUMMARY

In view of the ever increasing importance of the Doppler surveying technique and the higher accuracy expectations of the 1980's, it is very important to carefully analyze and define the various coordinate systems and the data processing methods. It is also significant to remove the gray areas involved, if any, which in turn would then clarify the resulting misinterpretation and many discrepancies.

The coordinate system using the BE is Modified NWL 10D by definition. The station positions available in this procedure would also be dependent for accuracy and definition on the data reduction procedure. If any investigator (and/or user) is then interested to establish the relationship of the project survey coordinate system with that of the PE or the WGS 72, each case should be studied on its own merit. For geodetic results and corresponding

accuracies, the BE coordinate system is definitely different from the PE system and the WGS 72 datum.

Table 3 results are self explanatory and the transformation clearly indicates that NWL 9D and NSWC 9Z-2 systems are different at meter and/or sub-meter level accuracies. This distinction should be reckoned into geodetic, geophysical and geodynamical studies as appropriate in each case.

As regards the question of the Z-axis bias in the Doppler System, the paper has highlighted some subtle mathematical model variations between Rapp and Rummel (1976), Huber (1979a and b) and Grappo (1980) and the possible reasons for different Z-bias values obtained in their studies. The results of the proposed additional investigations to study the involved model variations and their impact will be presented in the near future.

In the author's opinion some of the questions raised in this paper cannot be properly authenticated one way or the other at this time. There is much more involved in the Doppler System and its comparison with "external" data. The Doppler geodetic data have to be first upgraded for their consistency and properly refined in the involved geodetic definitions and the Z-shift study is one such problem which would need much more concentrated and extended effort.

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Table 1

GRAVITY FIELD REVISIONS IN DOPPLER SYSTEM

Date of Revision	Gravity Field	Information Source
20 February 1967	NWL 8D	Anderle (1976)
18 April 1968	NWL 8H	- do -
13 February 1970	NWL 9B	- do -
2 January 1973	NWL 10E	- do -
15 June 1977	NWL 10E-1*	Bowman (1976)

*The new model NWL 10E-1 consists of the NWL 10E gravity field with the addition of two new resonance gravity coefficients.

Table 2

COORDINATE SYSTEM REVISIONS IN DOPPLER SYSTEM

Date of Revision	Coordinate System	Information Source
20 February 1967	NWL 8E[1]	Anderle (1976)
19 January 1968	NWL 8F[2]	- do -
20 December 1970	NWL 9C[3]	- do -
18 October 1971	NWL 9D[4]	- do -
15 June 1977	NSWC 9Z-2[5]	Anderle (1980)

1. One year data from seven NNSS Satellites.

2. NWL 8E system transformed from the mean pole of 1966.7 to the CIO pole.

3. 40 days data in 1970 with the BIH preliminary pole position held fixed.

4. NWL 9C revised for three station heights.

5. Love number changed from 0.26 to 0.28 (Also see Tables 1 and 3).

TABLE 3

SEVEN PARAMETER TRANSFORMATION NWL 9D to NSWC 9Z-2

Translation			Rotation			Scale
DX (m)	DY (m)	DZ (m)	Omega (Arc Sec)	PSI (Arc Sec)	Epsilon (Arc Sec)	DS (ppm)
+0.5 ±0.4	-0.5 ±0.4	-0.9 ±0.4	-0.01 ±0.01	-0.01 ±0.01	-0.03 ±0.01	0.2 ±0.1

Note: (1) The transformation is in terms of NSWC 9Z-2 minus NWL 9D coordinates.

(2) The positive axes are towards Greenwich, East, and CIO.

(3) The rotations listed are about the 3rd, 2nd, and 1st axes respectively.

TABLE 4

SEVEN PARAMETER TRANSFORMATION NWL 10D(MOD) to NSWC 9Z-2

Translation			Rotation			Scale
DX (m)	DY (m)	DZ (m)	Omega (Arc Sec)	PSI (Arc Sec)	Epsilon (Arc Sec)	DS (ppm)
-0.6	-19.9	-22.3	+0.07	+0.06	0.62	-0.98
±2.8	± 3.7	± 4.8	±0.09	±0.18	±0.18	±0.39

Note: (1) The transformation is in terms of NSWC 9Z-2 minus NWL 9D Coordinates.

(2) The positive axes are towards Greenwich, East, and CIO.

(3) The rotations listed are about the 3rd, 2nd, and 1st axes respectively.